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Effects of wind, buoyancy and thermal expansion on a room fire with natural ventilation

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ABSTRACT

Effects of wind, buoyancy and thermal expansion on a room fire with natural ventilation provision were studied in this paper. The room was taken as a single zone of uniform temperature with two openings. A dimensionless system function derived from conservation of enthalpy was analysed and solved under different heat release rates. Air flow patterns of each scenario were also determined. Three steady air flow modes can be identified for fires of different heat release rates. At low heat release rates, the thermal expansion effect can be neglected. At medium heat release rates, the effects of all three factors should be taken into consideration. At high heat release rates, buoyancy effect can be neglected under strong wind. There are no specific experimental studies on the associated work due to resource limitation. However, results in this paper are compared with analytical expressions reported earlier without thermal expansion in the literature.

1. Introduction

With the growing interests in green or sustainable buildings, fire hazard in buildings with natural ventilation is a concern [1]. Wind, buoyancy and thermal expansion are driving forces of air and smoke movement [2] in a building. Note that places without large temperature difference between the indoor and the outdoor cannot induce strong stack effect for buildings of medium height. Burning a small quantity of plastics would produce a large quantity of smoke, but the temperature would not rise significantly. Smoke would then spread following air flow pattern inside the building. Fire and smoke spread in the modern green buildings with natural ventilation should be studied carefully.

Natural ventilation in a room with a small heat source was studied by taking the room as an opening system with a single zone of uniform temperature. In the study by Li and Delsante [3], analytical solutions were derived to calculate natural ventilation flow rates and air temperatures in a single-zone building with two openings. The effects of buoyancy, wind, solar radiation and thermal conduction loss through the building envelope were included. Lishman and Woods [4] studied the multiple steady states in a natural ventilation system with one upwind and one downwind opening under the effects of wind and buoyancy. The impact of the second downwind opening on indoor air flow was examined. It was found that if this new opening exceeds a critical area, the multiple steady states will vanish. This critical area is a function of the relative heights of the three windows. Analytical studies were verified by experiments. An expression for natural ventilation was developed by Larsen [5], which included the incident angle of the wind and the fluctuations in pressure at the opening. The multiple steady states in natural ventilation systems were also studied by Yuan and Glicksman [6,7], who also took both wind and buoyancy effects into account. The transition dynamics between stable steady states under perturbations were quantitatively described; the minimum perturbation time and the minimum perturbation magnitude were expressed; and the quantitative relation between the initial temperature and the final steady state were investigated. Lishman and Woods [8,9] examined the effect of wind action on the natural ventilation flow pattern. Expressions were developed to calculate the critical wind speed under steady states. Simulations with Computational Fluid Dynamics (CFD) were carried out by Gan [10] to investigate the interaction of wind and buoyancy in natural ventilation systems. This study provides references for the effective use of desirable wind effects and minimisation of adverse wind effects at the design stage.

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Nomenclature

A	wall area of system (m^2)
A_l	area of lower opening (m^2)
A_c	opening area (m^2)
A_u	area of upper opening (m^2)
B_{LR}	effect region width between L and R
C_d	discharge coefficient of opening
C_{dl}	discharge coefficient of lower opening
C_{du}	discharge coefficient of upper opening
C_P	specific heat capacity (J kg^{-1} K^{-1})
C_{Pa}	specific heat of air (J kg^{-1} K^{-1})
C_{Pl}	wind pressure coefficient of lower opening
C_{Pu}	wind pressure coefficient of upper opening
E	heat release rate of fire source (W)
E_L	thermalpower at point L (W)
E_R	thermal power at point R (W)
E_U	thermal power at point U (W)
g	acceleration of gravity (m s^{-2})
h	height difference between the upper and lower opening (m)
H_{LR}	effect region height between L and R
M	total mass (kg)
$\dot{m}_f$	mass flow rate of fuel burning (kg s^{-1})
$\dot{m}_{in}$	air mass flow rate entering the system (kgs^{-1})
$\dot{m}_{out}$	air mass loss rate from the system (kg s^{-1})
P	system pressure (Pa)
P_B	buoyancy effect (Pa)
P_B^{**}	dimensionless buoyancy
P_E	thermal expansion effect (Pa)
P_E^{**}	dimensionless expansion
P_l	wind pressure at lower opening (Pa)
P_u	wind pressure at upper opening (Pa)
P_W	wind pressure (Pa)
P_W^{**}	dimensionless wind pressure
q	volumetric flow rate (m^3 s^{-1})
Q_1,Q_2,Q_3,Q_L,$Q_{L'}$,$Q_{L''}$,Q_M,$Q_{M'}$,$Q_{M''}$, Q_N,$Q_{N'}$,$Q_{N''}$,$Q_{N'''}$,Q_O, $Q_{O'}$,Q_R,$Q_{R'}$,$Q_{R''}$	points in graphs for supporting discussions in the paper
r	dimensionless air mass
R_a	gas constant
T	system temperature (K)
T^{**}	dimensionless system temperature
T_a	initial room temperature (K)
T_M	system temperature at point M (K)
T_M^{**}	dimensionless temperature of the system at point M
T_N^{**}	dimensionless temperature of the system at point N
T_L	temperature of the system at point L (K)
T_L^{**}	dimensionless temperature of the system at point L
T_R	temperature of the system at point R (K)
T_R^{**}	dimensionless temperature of the system at point R
T_{ss1}^{**}	dimensionless temperature in steady state 1
T_{ss3}^{**}	dimensionless temperature steady state 3
T_1^{**}	dimensionless temperature of the system at point 1
T_2^{**}	dimensionless temperature of the system at point 2
T_3^{**}	dimensionless temperature of the system at point 3
t	time (s)
U	heat transfer coefficient ($Wm^{-2}K^{-1}$)
υ	external ambient wind speed (ms^{-1})
υ_B	buoyancy speed (ms^{-1})
υ_{cr}	critical ambient wind speed (ms^{-1})
υ_E	thermal expansion speed (ms^{-1})
υ_{ref}	reference wind speed (ms^{-1})
V	system volume (m^3)

Greek letters

β	air expansion coefficient
ε	dimensionless conductance
ΔH_a	heat release rate per kilogram of air (Wkg^{-1})
γ	dimensionless wind momentum
ρ	air density of the system (kgm^{-3})
ρ_a	initial state air density (kgm^{-3})
σ	dimensionless heat release rate per kilogram of air
τ	dimensionless time

Subscripts

a	air
B	buoyancy
c	common
cr	critical
d	discharge
E	expansion
f	fuel
in	flow into
l	lower
L	point L for supporting discussion
out	flow out
R	point R for supporting discussion
ref	reference
ss	steady state
u	upper
M,M′,M″,N′,N′,N″,O,O′,O″,L, L′,L″,R, R′,R″,E,E′,1,2,3	subscripts for points concerned for supporting discussion

Superscript

$**$	dimensionless quantity

All the above works are based on scenarios with small heat sources to produce small air temperature rise. The physical picture was simplified in an earlier study [11] which considered smoke movement in a ventilation-controlled fire. Natural ventilation was also provided in a single-zone compartment with two openings. In this paper, the team expanded the scope of earlier works [6,7] to study the effects of wind, buoyancy and thermal expansion on a natural ventilated compartment in a bigger fire with higher temperature rise. Work reported by Yuan and Glicksman [4,5] would be extended to study the natural ventilation system at high temperature. Wind, buoyancy and thermal expansion and their combined effects would be studied by identifying the characteristics of air flow triggered by a heat source at different heat release rates. Temperature variations could then be studied by including the resultant air flow directions.

Although single zone model has many assumptions such as constant room air temperature, analytical expressions deduced are very useful for working out design guides because of the simplicity. The equations can be applied to particular room geometry after tuning up with experimental studies on those specified fire scenarios. Taking wind effect on room fire as in this paper, wind action is a transient phenomenon that depends on the surrounding